Measurement of the $t\bar{t}$ Production Cross Section in $p\overline{p}$ Collisions at $\sqrt{s} = 1.96$ TeV with Displaced Vertex b-Tagging

Abstract

We present the measurement of the top quark pair production cross section in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV using 318 pb^{-1} of data obtained with the Collider Detector at Fermilab. *The cross section is measured in events with a leptonically decaying W boson in association with multiple jets.* In these events, the bottom quarks from the top quark decay are identified using a secondary vertex tagging algorithm. We measure a $t\bar{t}$ production cross section of $8.7^{+0.9}_{-0.9}$(stat)$^{+1.2}_{-0.9}$(syst) pb assuming a top quark mass of 178 GeV. We further establish with high significance the observation of $t\bar{t}$ production in fully reconstructed events, in which both b-quark jets are identified. **We further observe with high-significance $t\bar{t}$ production in fully reconstructed events, in which both b-quark jets are identified.** The top cross section measured in events with this signature is $10.1^{+1.6}_{-1.4}$(stat)$^{+2.1}_{-1.4}$(syst) pb.

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The top quark, discovered at the Fermilab Tevatron in $p\overline{p}$ collisions at $\sqrt{s} = 1.8$ TeV [1], completes the third fermion generation in the Standard Model (SM). The increased dataset of the Tevatron Run II allows for precise measurements of top quark production and decay characteristics. **The increased dataset in Run II at the Tevatron allows for precise measurements of top quark production and decay characteristics.** The determination of the top pair production cross section ($\sigma_{t\bar{t}}$) is a test of quantum chromodynamics (QCD). Theoretical QCD calculations predict $\sigma_{t\bar{t}}$ with an uncertainty smaller than 15% [2]. This level of precision has been achieved experimentally for the first time, and deviation from theory could indicate the presence of new physics.

This Letter reports the measurement of the top quark pair production cross section in the lepton + jets decay channel using the Collider Detector at Fermilab (CDF) with 318 pb^{-1} *of data collected between March 2002 and August 2004.* Top quarks are pair-produced in $p\overline{p}$ collisions at $\sqrt{s} = 1.96$ TeV through $q\overline{q}$ annihilation ($\sim 85\%$) or gluon fusion ($\sim 15\%$). The SM top quark has a lifetime too short for hadronization to occur and decays to a W boson and a bottom quark ($V_{tb} \sim 1$). In the lepton + jets channel, one W boson decays to an electron or a muon and a neutrino, while the other decays hadronically. The final state includes a charged lepton with high transverse momemtum (p_T), large missing transverse energy ($\not\!\!E_T$) from the undetected neutrino, two light-quark jets from the hadronic W, and two b-quark jets. Identification of at least one b-quark jet (b-tagging) allows for a significant increase in the signal-to-background ratio.

When both b-quark jets are identified, $t\bar{t}$ events can be fully reconstructed; the only remaining ambiguities are the longitudinal component of the neutrino momentum and the $b - W$ pairing. The double b-tagged sample has been increased by a factor of seven since our last $\sigma_{t\bar{t}}$ publication [3], benefiting from recent improvements in our b-tagging algorithm and the larger integrated luminosity. For the first time, we observe $t\bar{t}$ production in the double b-tagged sample with a significance over 5σ. We perform the measurement with a new, high-efficiency version of the secondary vertex b-tagging algorithm (`SecVtx`) [3]. The result is cross-checked with an updated version of the original `SecVtx` algorithm.

The CDF detector is a general-purpose particle detector located at one of the two interaction points at the Tevatron Collider. Its detailed description can be found elsewhere [4]. We briefly describe here the components most relevant to this analysis.

Inside a 1.4 T solenoidal magnetic field, the Central Outer Tracker (COT) [5] and a three-detector silicon system [6] provide tracking information. The COT is a large cylindrical open cell drift chamber that covers the pseudorapidity range $|\eta| < 1.1$ and consists of 96 layers that are grouped in eight alternating superlayers of axial and stereo wires. The COT measures 310 cm in length, with an inner radius of 41 cm extending to a radius of 138 cm, providing a large lever arm for curvature measurements. The measured momemtum resolution is $\sigma(p_T)/p_T \sim 0.15\% p_T$ (GeV/c)$^{-1}$.

The Silicon Vertex detector (SVXII) is the main CDF silicon detector. It measures 90 cm in length and consists of five concentric layers of double-sided micro-strip silicon sensors covering radii from 2.5 cm to 10.6 cm. The SVXII provides tracking information in three spatial dimensions, with an impact parameter resolution of about 40 μm (including a 30 μm contribution from the beamspot). The Intermediate Silicon Layer detector (ISL) is located between the SVXII and the COT; it extends the tracking coverage at pseudorapidity $|\eta| > 1.1$. One single-sided layer of silicon micro-strip sensors (L00) is mounted directly on the beampipe. This detector provides a position measurement approximately 1.3 cm from the interaction point, improving the impact parameter resolution for low-p_T tracks. Outside the solenoid, electromagnetic and hadronic calorimeters, arranged in a projective tower geometry, surround the tracking volume and are used to identify electrons and jets over the range $|\eta| < 3.6$. The electron energy is measured in the central electromagnetic calorimeter (CEM) ($|\eta| < 1.1$) and the end-plug electromagnetic calorimeters ($1.1 < |\eta| < 3.6$). Outside the calorimeters, three systems of drift chambers in the region $|\eta| < 1.0$ provide muon identification.

The data were collected with an inclusive high-p_T lepton trigger that requires an electron (muon) with $E_T > 18$ GeV ($p_T > 18$ GeV/c). The trigger efficiency is $\sim 96\%$ for electrons and $\sim 90\%$ for muons. Inclusive lepton + jets samples are selected by requiring exactly one lepton that satisfies tight lepton identification criteria, and $\not\!\!E_T > 20$ GeV. Electron events are selected by requiring one isolated [8] electron with transverse energy $E_T > 20$ GeV in the CEM. Muon events are required to have one isolated muon with transverse momentum $p_T > 20$ GeV/c in the central region. Events with a high-p_T lepton consistent with a Z boson decay, cosmic ray, or conversion are removed. The event primary vertex is required to be within 60 cm of the nominal interaction position and consistent with the high-p_T lepton. In addition, we require the transverse mass of the lepton and the missing energy ($M_T^W = \sqrt{E_T(l) + E_T(\nu))^2 - (\vec{P}_T(l) + \vec{P}_T(\nu))^2}$) to be consistent with W boson production, $M_T^W > 20$ GeV.

To extract the $t\bar{t}$ signal from this inclusive sample, we require at least three jets with $|\eta| < 2$ and corrected [9] transverse energy greater than 15 GeV, clustered with a cone-based algorithm with a cone size $\Delta R = \sqrt{\Delta\phi^2 + \Delta\eta^2} = 0.4$. On average, events from $t\bar{t}$ production have a larger total transverse energy than background events; therefore, for events with at least three jets, we require the scalar sum of all transverse energy in the event (H_T) to be larger than 200 GeV. After this selection there are 46,353 (39,203) W events remaining in the electron (muon) data sample. Table I shows the event count at this stage (pretag) sorted by the number of jets in the event.

This dataset is dominated by real W bosons with associated light-flavor production. To improve the $t\bar{t}$ signal significance, we require at least one jet to be b-tagged (at least two for the double b-tagged analysis) by identifying displaced secondary vertices using a new version of the `SecVtx` algorithm. We have improved the algorithm by relaxing the input track selection requirements and tightening the final secondary vertex criteria. This allows more tracks from real b-decays to be considered for the secondary vertex fit while maintaining a low fake rate. Secondary vertices are reconstructed from at least two or three tracks with impact parameter significance $d_0/\sigma_{d_0} > 3.0$ or 2.0, respectively. *Contributions from K_S^0 and Λ decays, and interactions in the inner detector material are reduced using a combination of track and vertex selection criteria. We reject light flavor tags tags due to K_S^0 or Λ and material interactions.* A jet is tagged if the reconstructed secondary vertex has a decay length significance $L_{2D}/\sigma_{2D} > 6.0$ (positive tag). The probability of misidentifying a light flavor jet as a b-jet due to detector resolution (**mistag**) is estimated from secondary vertices with $L_{2D}/\sigma_{2D} < -6.0$ (negative tag). A version of the algorithm with more stringent requirements was used for the top quark mass measurements (ref) and it is used here as a cross check. The tighter `SecVtx` version uses tracks with $d_0/\sigma_{d_0} > 3.5$ in the two-track vertices, and requires $L_{2D}/\sigma_{2D} > 7.5$.

The $t\bar{t}$ acceptance is calculated from a combination of data and Monte Carlo. We use `PYTHIA` simulation [10] with `CTEQ5L` parton distribution functions [11] and assume $M_{top} =$ 178 GeV/c^2, the world average top mass measurement from Run I. The CLEO QQ Monte Carlo program [12] is used to model the decays of bottom and charm hadrons. These events are passed through a simulation of the CDF detector and subjected to the same selection requirements as the data. The total acceptance, including the branching fraction, is calculated as the product of the kinematic (including lepton identification) and geometric acceptances and the trigger and tagging efficiencies. The efficiency for identifying isolated, high-p_T leptons is scaled to the value measured in Z-boson data. The total acceptance in the electron (muon) channels for events before b-tagging is $(3.8 \pm 0.3)\%$ ($(2.8 \pm 0.2)\%$).

The tagging efficiency is estimated from the $t\bar{t}$ simulation and corrected to match the efficiency in data. The $t\bar{t}$ per-event tagging efficiency for one or more b-tags is $(69 \pm 5)\%$, while the double b-tag efficiency is $(23 \pm 3)\%$. We include any tag in $t\bar{t}$ Monte Carlo events, including those c-quark jets from the hadronic decay of the W and other light-flavor jets. The total $t\bar{t}$ event efficiency is then the product of the Monte Carlo efficiency and an appropriate scale factor that corrects the different efficiencies for tagging bottom, charm and light-flavor jets to their values in data.

The uncertainty on the b-tagging scale factor leads to a 6% systematic uncertainty on the single-tag cross section and it is the dominant uncertainty for the double-tag analysis (13.4%). This systematic is derived from charm and light-flavor contamination in the data sample and from the extrapolation to higher jet-E_T from the jets in the the low-p_T lepton sample where the scale factor is measured. Other important systematic uncertainties in the acceptance calculation come from lepton isolation (5%), jet energy scale ($\sim 5\%$), lepton identification ($\sim 2\%$), parton distribution functions (2%), Monte Carlo generator (2%), and modeling of initial and final state radiation (1%).

The major source of background in the tagged lepton + jets sample is the production of W bosons in association with multiple jets. Smaller contributions come from generic QCD production with a fake W and lower-rate electroweak processes such as single top production, diboson production (WW, WZ, ZZ) associated with jets, and $Z \to \tau\tau$. Tables I and II summarize the composition of the single-tag and double-tag samples sorted by the number of jets in the events. In the double b-tagged case, the background contribution is very small and dominated by production of W bosons associated with heavy flavor, $Wb\bar{b}$, $Wc\bar{c}$ and Wc. In the single b-tagged sample, W + jets events where one light-quark jet is misindentified as a b-jet become as significant as W + heavy flavor production.

The fractions of $Wb\bar{b}$, $Wc\bar{c}$, and Wc processes relative to the inclusive W + jets process are estimated with ALPGEN/HERWIG Monte Carlo samples. The expected number of $Wb\bar{b}$, $Wc\bar{c}$ and Wc events is estimated by multiplying those fractions by the number of pretag events, after removing the contributions from all the other backgrounds and $t\bar{t}$ production. The tagging efficiency for such events is measured in simulation and corrected with **by** the b-tag scale factor.

We estimate the light-flavor contribution ($W+LF$) by applying the parametrized generic jet tag rate to the lepton + jets dataset. The raw prediction must be scaled to account for the heavy flavor contribution to the parametrized tag rate, and we estimate this correction to be roughly 20%. The light flavor contribution to the double-tagged sample is very small, but is determined by looking at the prediction from the parametrization only in events with at least one positive tag. In both cases, the prediction is scaled by the fraction of the data sample not attributed to a physics process with real heavy flavor.

The background from events that do not contain a real W boson (non-W) is estimated from data. We assume that the isolation of the lepton and the missing energy are uncorrelated. Thus, we extrapolate from regions of non-isolated leptons and lower missing energy (which are enriched in non-W events) to the $t\bar{t}$ signal region to determine the expected contribution to the pretag and tagged samples.

Finally, we estimate the backgrounds due to dibosons, single top, and $Z \to \tau\tau$ using Pythia Monte Carlo assuming their theoretical cross sections (ref). may have signatures similar to $t\bar{t}$. The calculation follows straightforwardly from the signal estimation, assuming the theoretical cross sections (ref) are suficiently precise. These backgrounds are very small for the single-tag analysis and negligible for double-tags.

Our results are tabulated in Tables I and II. Figures 2 and 3 show the observed and expected number of events versus jet multiplicity. Those backgrounds that are calculated as a fraction of the number of $W+$ jet events are corrected iteratively to account for the $t\bar{t}$ content in the sample [3]. The total corrected background in the signal region with at least one b-tag (two b-tags) is 46 ± 9 (4.1 ± 2.5) events. We observe 174 $W+ \geq 3$ jets events with at least one b-tag and 54 events with $\geq$ two b-tagged jets. We interpret this excess of $W+ \geq 3$ jet events over the background expectation as $t\bar{t}$ signal.

Assuming a top quark mass of 178 GeV, we measure $\sigma_{t\bar{t}} = 8.7^{+0.9}_{-0.9}(\mathrm{stat})^{+1.2}_{-0.9}(\mathrm{syst})$ pb, where the systematic uncertainty includes a 5.9% contribution from the integrated luminosity estimate. The acceptance and efficiency both have a small dependence on the top quark mass; the cross section measurement changes by ± 0.08 pb for each ∓ 1 GeV/c^2 change in the assumed top mass from the initial value of 178 GeV/c^2. The measurement with double b-tagged events is $\sigma_{t\bar{t}} = 10.1^{+1.6}_{-1.4}(\mathrm{stat})^{+2.1}_{-1.4}(\mathrm{syst})$ pb.

The measurement with the original `SecVtx` tagger follows the same analysis procedure and is used to cross check these results. We observe 138 (33) events with at least one (two) b-tags in the signal region, compared to a background of 25 ± 5 (3 ± 2) events. This gives $\sigma_{t\bar{t}} = 8.7^{+0.9}_{-0.9}(\mathrm{stat})^{+1.2}_{-0.9}(\mathrm{syst})$ pb and $8.7^{+1.8}_{-1.6}(\mathrm{stat})^{+1.9}_{-1.3}(\mathrm{syst})$ pb for single- and double-tagged events, both in good agreement with the cross section results above.

In summary, we have measured the $t\bar{t}$ production cross section in $p\bar{p}$ collisions at $\sqrt{s} =$ 1.96 TeV using the lepton plus jets events and improved lifetime b-tagging tools. Our measurement of $\sigma_{t\bar{t}} = 8.7^{+0.9}_{-0.9}(\mathrm{stat})^{+1.2}_{-0.9}(\mathrm{syst})$ pb assumes the top quark mass of 178 GeV and is in good agreement with SM theoretical expectations.

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TABLES

TABLE I. Summary of event yields and background expectations for events with at least one b-tagged jet. These numbers assume the measured $t\bar{t}$ cross section of 8.7 pb.

	$W+1$ jet	$W+2$ jets	$W+3$ jets	$W+4$ jets	$W+\geq 5$ jets
Pretag	30283	4676	324	142	34
Dibosons	6.3 ± 0.9	11.8 ± 1.7	1.7 ± 0.3	0.46 ± 0.12	0.15 ± 0.04
t (s-ch)	2.0 ± 0.28	5.8 ± 0.8	0.8 ± 0.11	0.16 ± 0.02	0.03 ± 0.01
t (t-ch)	6.0 ± 2.6	7.4 ± 3.2	1.0 ± 0.4	0.23 ± 0.10	0.05 ± 0.02
$Wb\bar{b}$	115 ± 35	63 ± 19	6.1 ± 1.7	1.4 ± 0.8	0.17 ± 0.09
$Wc\bar{c}$	46 ± 13	30 ± 9	3.8 ± 1.2	1.1 ± 0.4	0.14 ± 0.04
Wc	129 ± 33	34 ± 9	3.0 ± 0.8	0.82 ± 0.22	0.10 ± 0.03
$W+LF$	261 ± 57	101 ± 22	14.5 ± 3.2	4.4 ± 1.0	0.62 ± 0.14
Non-W	58 ± 12	24 ± 5	2.8 ± 0.7	2.5 ± 0.8	0.20 ± 0.18
Bkgd	624 ± 100	277 ± 43	33.7 ± 5.8	11.2 ± 2.4	1.45 ± 0.58
$t\bar{t}$	3.5 ± 0.4	27.9 ± 3.2	52.7 ± 5.8	56.6 ± 6.1	18.1 ± 2.0
Total	628 ± 100	305 ± 43	86.4 ± 8.2	67.8 ± 6.6	19.6 ± 2.1
Data	722	346	80	71	23

TABLE II. Summary of event yields and background expectations for events with at least two b-tagged jets. These numbers assume the measured $t\bar{t}$ cross section of 10.1 pb.

	$W+2$ jets	$W+3$ jets	$W+4$ jets	$W+\geq 5$ jets
Dibosons	0.68 ± 0.12	0.11 ± 0.02	0.041 ± 0.010	0.017 ± 0.005
t (s-ch)	1.8 ± 0.3	0.29 ± 0.05	0.05 ± 0.01	0.010 ± 0.002
t (t-ch)	0.36 ± 0.16	0.24 ± 0.10	0.07 ± 0.03	0.016 ± 0.008
$Wb\bar{b}$	11.4 ± 3.7	1.3 ± 0.4	0.21 ± 0.08	0.010 ± 0.004
$Wc\bar{c}$	0.93 ± 0.41	0.22 ± 0.11	0.07 ± 0.04	0.004 ± 0.002
Wc	0.51 ± 0.15	0.05 ± 0.03	0.021 ± 0.012	0.001 ± 0.001
$W+LF$	2.6 ± 1.3	0.03 ± 0.11	0.00 ± 0.12	0.16 ± 0.23
Non-W	0.59 ± 0.59	0.28 ± 0.28	0.5 ± 0.5	0.35 ± 0.35
Bkgd	18.8 ± 4.3	2.5 ± 1.2	1.0 ± 0.8	0.6 ± 0.5
$t\bar{t}$	7.5 ± 1.3	18.4 ± 3.2	23.6 ± 4.1	7.8 ± 1.4
Total	26.4 ± 4.5	21.0 ± 3.4	24.6 ± 4.2	8.4 ± 1.4
Data	30	23	25	6

FIGURES

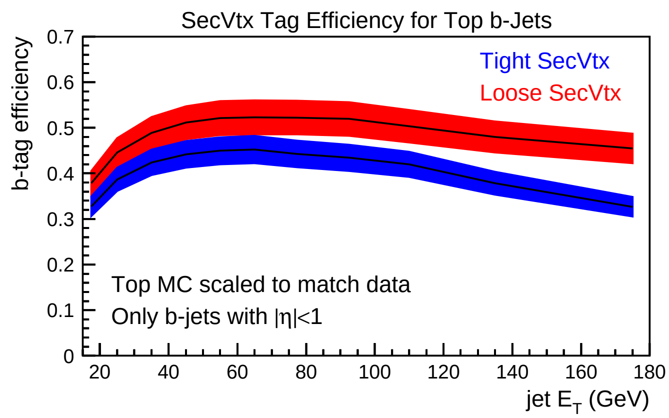

FIG. 1. **SecVtx** tagging efficiency as a function of jet E_T for $t\bar{t}$ b-quark jets with $E_T > 15$ GeV and $|\eta| < 1$. Comparison between the two **SecVtx** tagger operation points.

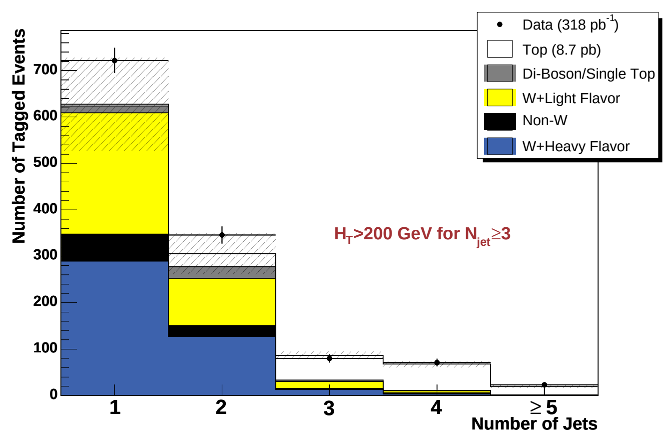

FIG. 2. Summary of background and signal for the single-tag analysis.

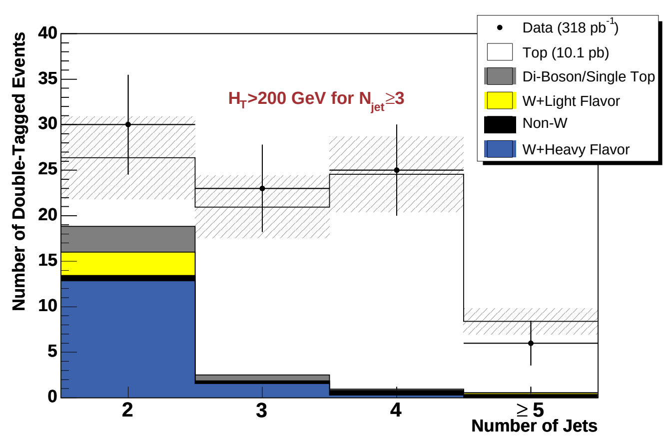

FIG. 3. Summary of background and signal for the double-tag analysis.

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